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The Impact of Mergers on the Survival and Abundance of Disk-Dominated Galaxies

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Abstract. We study the formation of disk-dominated galaxies in a ΛCDM universe. Their existence is considered to be a challenge for the ΛCDM cosmology, because galaxy mergers isotropize stellar disks and trigger angular momentum transport in gas disks, thus fostering the formation of central stellar spheroids. Here, we postulate that the formation of stellar spheroids from gas-rich disks is controlled by two parameters that characterize galaxy mergers, the mass ratio of merging dark matter halos, and the virial velocity of the larger merging halo. We utilize merger histories generated from realizations of the cosmological density field to calculate the fraction of dark matter halos that have avoided spheroid formation, and compare the derived statistics with the spheroid occupation fractions in surveys of nearby galaxies. We find, for example, that the survival rate of disk-dominated galaxies in ΛCDM is just high enough to explain the observed fractional representation of disk-dominated galaxies in the universe if the only mergers which lead to central spheroid formation are those with mass ratios $M_2/M_1 > 0.3$ and virial velocities $V_{\rm vir,1} > 55\ {\rm km\ s^{-1}}$. We discuss the physical origin of this criterion, and show that the dependence of the disk-dominated fraction on galaxy mass provides a further test of the merger hypothesis.

1. Introduction

Disk-dominated galaxies with little or no bulge are frequently cited as a challenge to the ΛCDM cosmology (e.g. Kautsch et al. 2006). In ΛCDM cosmology, galaxy-hosting halos grow hierarchically by mergers. Major mergers destroy disks and create elliptical galaxies/classical bulges. On the other hand, pseudobulges are thought to be created by secular evolution, not by major mergers (Kormendy & Kennicutt 2004). We consider what the requirements for bulge-forming mergers must be in order for the merger history of galactic halos in ΛCDM to account statistically for the observed fraction of galaxies today which are "disk-dominated" – i.e., those with either no bulge or only a pseudobulge. [For additional details, see, Koda et al. (2009).]

2. A Simple Merger Hypothesis

We explore a simple model in which bulge formation due to merger is controlled by two parameters, mass ratio $\mu = M_2/M_1 (\leq 1)$ and the virial velocity of the larger halo, $V_{\rm vir,1}$. The hypothesis of the model is that a bulge forms if and only if,

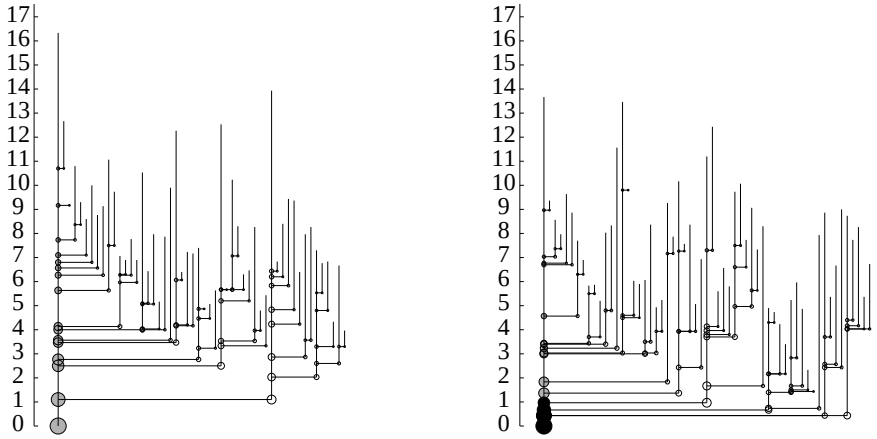

Figure 1. Examples of merger trees. Gray circles represent disk-dominated galaxies and black circles represent galaxies with classical bulges, respectively, under a bulge-forming criterion $\mu_{\rm crit} = 0.3$, $V_{\rm vir,crit} = 55$ km s^{-1}. Radii of circles are proportional to $M^{1/3}$. Mergers with $\mu < 0.05$ are not plotted in the figure. Vertical axis label is redshift.

$$\mu > \mu_{\rm crit} \text{ and } V_{\rm vir,1} > V_{\rm vir,crit}. \quad (1)$$

Motivation: Mergers which make bulges are generally assumed to require a merging-halo mass ratio, μ, above some threshold, $\mu_{\rm crit}$, consistent with N-body and some hydro simulations (e.g., Bournaud, Jog, & Combes 2005; Cox et al. 2008). We hypothesize here an additional dependence on $V_{\rm vir,1}$, the virial velocity of the larger halo. The virial velocity characterizes gas dynamical effects. Bulge formation requires angular-momentum transport, which strong shocks can promote. Shock-induced radiative cooling and compression also promote gravitational instability. The strength of merger shocks is characterized by the Mach number $\mathcal{M} \propto V_{\rm vir}$. If the IGM was pre-heated by reionization, gas pressure can prevent gas from collapsing into galaxies ("Jeans-mass filtering," Shapiro et al. 1994) if the virial velocity is too low. The threshold value of this Jeans-mass filtering is uncertain ($\sim 30 - 80$ km s^{-1}, e.g., Okamoto et al. 2008, and references therein). Mergers of pre-existing stellar systems with $\mu > \mu_{\rm crit}$ still require $V_{\rm vir,1} > V_{\rm vir,crit}$ to make enough stars before merger (i.e., star formation requires gaseous baryons but halos may not retain if $V_{\rm vir}$ too low).

Method: Merger Tree. We generate merger trees for the galactic halos in a comoving volume 40 Mpc using a publicly available code PINOCCHIO (Monaco et al. 2002) based on Lagrangian perturbation theory. The code gives halo masses and their merger histories that are in good agreement with N-body simulations, but with less computation. We follow the most massive progenitor of each halo, in mass range $5 \times 10^{10} M_\odot < M < 10^{12} M_\odot$, and check the bulge-forming condition (Eq. 1) for all mergers (see Fig. 1). We assume that a halo hosts a disk-dominated galaxy if none of its mergers satisfies the bulge formation

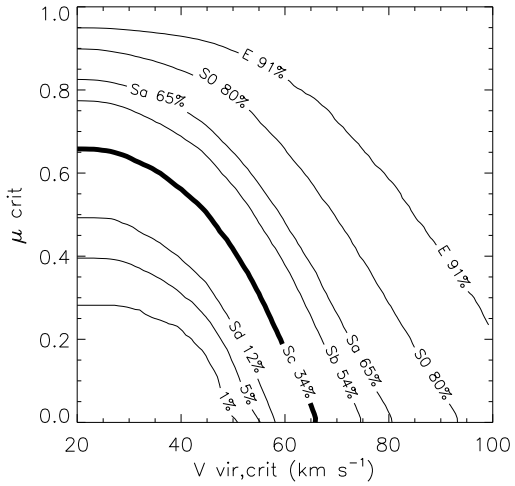

Figure 2. The fraction of disk-dominated galaxies that results from bulge formation criteria characterized by the critical merger mass ratio, $\mu_{\rm crit}$, and the critical virial velocity of the larger halo at merger, $V_{\rm vir,crit}$. The points along the bold contour "Sc 34%" (e.g., $\mu_{\rm crit} = 0.3, V_{\rm vir,crit} = 55$ km s^{-1}) constitutes our theoretical expectation for the bulge-forming threshold criteria that is compatible with observation (See § 3.).

criterion. We vary $\mu_{\rm crit}$ and $V_{\rm vir,crit}$ to see which critical values are consistent with the observed fraction of disk-dominated galaxies.

3. Results

Figure 2 shows the fraction of galaxies without classical bulge (disk-dominated galaxies) as a function of the bulge formation criterion ($\mu_{\rm crit}, V_{\rm vir,crit}$), which is the result of the model described in § 2. Some of the contours are also labeled by the morphological type of galaxy in the *Tully Catalogue* [1] such that the observed fraction of galaxies of that morphological type or later equals the theoretical fraction of disk-dominated galaxies. We assume that galaxies of type Sc and later are the disk-dominated population. Fraction of Sc or later is 34% in the Tully subsample, which is also consistent with other observations (e.g., Kautsch et al. 2006; Barazza et al. 2008). So, the ($\mu_{\rm crit}, V_{\rm vir,crit}$)-values for which our bulge formation hypothesis predicts the observed disk-dominated-galaxy fraction 34% are shown by the bold contour in Fig. 2, labelled "Sc 34%," e.g., $\mu_{\rm crit} = 0.3, V_{\rm vir,crit} = 55$ km s^{-1}. Somewhat smaller $\mu_{\rm crit}$ and larger $V_{\rm vir,crit}$, or vice versa, are also plausible. However, $V_{\rm vir,crit}$ cannot be larger than 65 km s^{-1} because it will overproduce disk-dominated galaxies.

4. Conclusion

In order to explain the observed fraction of disk-dominated galaxies within ΛCDM cosmology, we propose a bulge-forming criterion such that only those mergers with $M_2/M_1 > \mu_{\rm crit} \sim 0.3$ and $V_{\rm vir,1} > V_{\rm vir,crit} \sim 55$ km s^{-1} form bulges. The validity of this bulge formation criterion needs to confirmed by

[1] http://haydenplanetarium.org/universe/duguide/exgg_tully.php

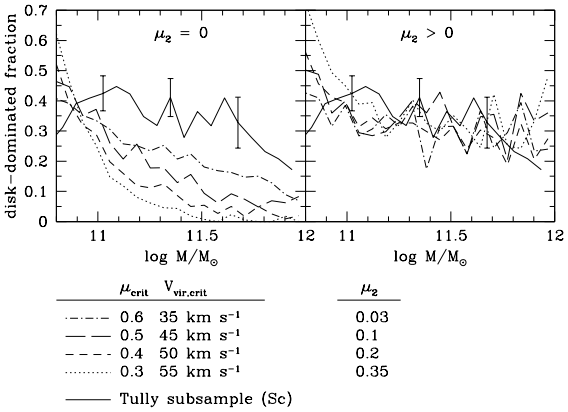

Figure 3. Disk-dominated fraction as a function of galaxy-hosting halo mass for the two-parameter model ($\mu_{\rm crit}, V_{\rm crit}$) (*left panel*) and the three-parameter model with additional parameter μ_2 (*right panel*), in which we assume that a merger remnant would not be observed as a classical bulge if its mass were smaller than μ_2 times present halo mass. Solid line is the observed fraction of Sc and later in the Tully subsample. Our model with only two parameters (*left*) does not agree with the observed mass dependence, but the agreement becomes reasonably good by introducing the third parameter μ_2 (*right*).

further study of low-mass mergers ($V_{\rm vir,1} \sim 30 - 60$ km s^{-1}) by, e.g., hydro simulations. The mass dependence of the disk-dominated fraction (Fig. 3) can be explained, too, if merger remnants which are small compared to the present halo mass are too small to be observed as a classical bulge. Future surveys of bulgeless/pseudobulged galaxy fraction as a function of mass would be useful for determining the bulge-formation criterion and testing this hypothesis.

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